Journal of Plant Production and Sustainability (2025) 1(1): 1-11

RESEARCH PAPER

Assessment of growth and yield traits under irrigated and rainfed environments for genotypes selection in barley (*Hordeum vulgare* L.)

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Abstract

Barley is increasingly valued as a climate-resilient cereal crop, especially in regions like Pakistan where wheat production cannot meet rising food demands. Despite its potential, barley cultivation in the country has declined due to limited research and investment in high-yielding, stress-tolerant varieties. This study aimed to evaluate the growth and yield performance of different barley (*Hordeum vulgare*) genotypes under rainfed and irrigated conditions to identify promising lines for cultivation in variable environments. In this study, twelve barley genotypes were evaluated across two consecutive cropping seasons (2019–20 and 2020–21) under rainfed and irrigated conditions. The experiment followed a split-plot design arranged in a randomized complete block design (RCBD) with three replications. Irrigation regimes were assigned to main plots and applied at critical growth stages under irrigated conditions, while subplots represented different treatments, including rainfed plots that relied solely on natural rainfall. The findings of this study indicate that germination remained high across both environments. Under irrigated conditions, the average germination percentage was 95.9%, while under rainfed conditions, it slightly increased to 96.4%. Genotypes such as Sultan-17 (97% under both conditions), Rakhshan-10 (97% irrigated, 98 % rainfed), and JAU-21 (97% under both conditions) consistently exhibited strong germination and early vigor across both environments. Days to heading (101 days) were earlier under rainfed conditions, indicating drought-induced earliness, with Bajwar-2000 and MPT-V2 emerging as early heading genotypes. Maturity duration (149 days) remained stable across both environments. Drought stress led to reductions in plant height, spike length, biomass, and grain yield. However, certain genotypes, especially Rakhshan-10, Sultan-17, and Bajwar-2000, maintained superior performance under both moisture regimes. JAU-21 recorded the highest grain yield (5680 kg ha^{-1}) under normal irrigation, while Bajwar-2000 showed the highest yield (4932 kg ha^{-1}) under rainfed conditions. These findings highlight genotypic variation in drought tolerance and suggest the potential of specific lines for cultivation in water-limited environments. © 2025 The Author(s)

Keywords: Barley genotypes, Drought tolerance, Grain yield, Growth characters, Normal irrigation, Rainfed agriculture

Citation: Rafique, A., Iqbal, A., Riaz, M., & Abbas, H. G. (2025). Assessment of growth and yield traits under irrigated and rainfed environments for genotypes selection in barley (*Hordeum vulgare* L.). *Journal of Plant Production and Sustainability, 1*(1), 1–11.

Introduction

Barley (*Hordeum vulgare*) is among the earliest domesticated cereal crops, with evidence of its cultivation in Eurasia dating back approximately 10,000 years (Zohary & Hopf, 2000). Historically, it has served multiple purposes including use as animal feed and as an ingredient in various nutritious food products. Barley is frequently used in soups, stews, and traditional breads across different cultures. Additionally, it is often processed into malt through a long-established method. As of 2023, global production of barley reached 146 million tonnes, making it the fourth most produced grain after maize, rice, and wheat (FAO STAT, 2023). In Pakistan, wheat is the primary staple food; however, domestic production is not keeping pace with the rising population, currently estimated at 255 million. This growing disparity between supply and demand highlights the need for an alternative cereal crop to help alleviate pressure on wheat supplies. In the main wheat-growing regions, the cropping systems typically include wheat-rice and wheat-cotton in irrigated zones, and wheat-peanut in rain-fed areas. Other challenges contributing to reduced crop yields include soil salinity and unpredictable, extreme weather patterns (Khokhar & Teixeira da Silva, 2012). According to Kilic et al. (2010), barley's early maturation and ability to avoid late-season drought make it a promising option for cultivation in regions with limited irrigation resources.

Barley is increasingly recognized as a climate-resilient crop, and its promotion is being recommended in Pakistan to help ensure sustainable cereal production in the face of climate change and global warming. Unfortunately, due to limited research and lack of policy focus, barley cultivation in Pakistan has declined significantly, from an export of 94.6 thousand tons in the 1970s to an import of about 40 thousand tons in 2019. The major challenge for barley in Pakistan is the lack of investment in developing high-yielding, industry-oriented cultivars. To address this, several barley varieties have already been developed by local research institutes, including Jau-83,

Jau-87, Haider-93, Jau-2017, and Sultan-2017. The Planning Commission of Pakistan (PCP) and the Centre for Agriculture and Bioscience International (CABI) have strongly recommended interventions to develop new two-row barley varieties with improved malting quality and resistance to biotic and abiotic stresses (Abid et al., 2020). Ongoing efforts are focused on the development of both two-row and six-row hulled and hull-less high-yielding barley varieties with superior grain quality, aiming to support the domestic brewery industry and reduce barley grain imports currently valued at approximately US$12 million.

Abiotic stresses, including drought, salinity, extreme temperatures (both heat and cold), and nutrient deficiencies, can significantly decrease crop yields and limit the geographic and edaphic ranges where commercially important species can be cultivated (Baig et al., 2018; Zaman & Qureshi, 2018; Abbas & Shafique, 2019; Shah et al., 2019; Iqbal & Qureshi, 2021; Mehmood et al., 2022; Ferioun et al., 2023; Azam et al., 2023). Among these, drought stress is one of the most critical constraints on agricultural productivity. The seriousness of drought stress depends on its timing, duration and intensity (Fatemi et al., 2022). Drought stress tolerance is a complex inherited trait controlled by several genetic loci and is often confounded by changes in plants phenology (Fleury et al., 2010; Hebbache et al., 2024). Water deficit happens when water potentials in the rhizosphere are sufficiently negative to decrease water availability to sub- optimal levels for crop growth and development (Elakhdar et al., 2022). The combination of continued impact of drought and high temperature impairs the photosynthesis during the daytime and increases the surface temperatures in the night, which in turn increases the photo respiratory losses and thus the productivity (Asadi et al., 2023).

Currently, agricultural activities account for about 75% of global freshwater use, with irrigation alone responsible for over 90% of water consumption in many developing nations (Yang et al., 2010). This heavy reliance on water resources poses a serious risk to the sustainability of crop production, particularly as water scarcity is projected to impact approximately 67% of the global population by 2050. The combined pressures of rapid population growth and increasing climate variability are expected to significantly challenge global food security. According to Lobell and Gourdji (2012), simulation studies have effectively predicted the impact of climate change on yields of major global crops. To safeguard agricultural productivity and meet the food demands of a growing global population, substantial investments in crop adaptation strategies will be essential.

Drought stress negatively impacts the grain yield of barley by adversely affecting key yield components such as the number of plants per unit area, number of spikes and grains per plant or area, and 1000-kernel weight. These components are influenced at various stages of plant development (Haddadin, 2015; Thakur et al., 2022). Barley genotypes that flower earlier tend to outperform later-flowering types, often resulting in higher yields (Al-Ajlouni et al., 2016). Research has shown that drought-tolerant genotypes not only maintain high productivity under water-limited conditions but also perform well under adequate irrigation (Haddadin, 2015). Such genotypes hold potential as valuable parental lines in breeding programs aimed at enhancing drought tolerance in barley (Behrooz et al., 2023). Identifying and selecting genotypes with drought resilience remains a critical objective in plant breeding, as it enables the exploitation of genetic diversity for developing stress-tolerant cultivars (Thakur et al., 2022; Hebbache et al., 2024). In the current study, various barley genotypes were evaluated across two growing seasons under both rainfed and irrigated conditions. The goal of this research study was to identify genotypes suitable for cultivation in the Faisalabad region of Pakistan, based on their responses to water availability and their performance in terms of yield, grain quality, and yield components.

Materials and Methods

Experimental site

The present study was conducted over two consecutive cropping seasons (2019–20 and 2020–21) at the Experimental Station of the Wheat Research Institute, Ayub Agricultural Research Institute (AARI), Faisalabad, Pakistan. The experimental site is geographically located at 31°39′N latitude and 73°04′E longitude with an altitude of 183.35 meters above sea level. The region is classified as semi-arid with relatively hot summers and cool winters. Weather data, including rainfall and temperature, were monitored throughout both growing seasons (Tables 1 and 2).

Plant materials

Twelve barley genotypes were used in this experiment (Table 3). These included advanced lines selected for their diversity in growth and yield performance. All genotypes were sown under two contrasting moisture regimes to assess their response to water availability.

Experimental design and treatments

The experiment was conducted using a split-plot design arranged in a randomized complete block design (RCBD) with three replications. Two moisture regimes were assigned to the main plots: normal irrigation (NI), where three irrigations were applied at the tillering, booting, and grain filling stages, and rainfed (Barani) conditions, where no supplemental irrigation was provided, and the crop depended solely on natural rainfall. The subplots comprised twelve barley genotypes, each sown in a plot measuring 1.8 m × 5.0 m (9.0 m²) with six rows spaced 30 cm apart. A uniform seed rate of 85 kg ha^{-1} was used, and

sowing was carried out manually with a hand drill during the second week of November in both growing seasons.

Crop husbandry

Fertilizer was applied using urea and diammonium phosphate (DAP) to supply 80 kg N ha^{-1} and 60 kg P_2O_5 ha^{-1}, respectively. Under irrigated conditions, urea was applied in split doses, while under rainfed conditions, the full dose of urea was applied at sowing. Weeds were managed manually, and no chemical pest control was needed during the experiment. The soil at the site typical of the Faisalabad region is silty clay loam, slightly alkaline, and moderately fertile.

Table 1 Weather conditions during barley crop seasons (2019-20) at Wheat Research Institute, Faisalabad, Pakistan

Month	Average maximum temperature	Average minimum temperature	Average relative humidity	Rainfall	Average sunshine hours
November	26.3 °C	12.8 °C	55.4 – 82.2%	3.0 mm	5 h + 19 min
December	17 °C	6.0 °C	0.4 - 67%	7.0 mm	3 h + 23 min
January	17.3 °C	5.5 °C	0.4 – 60.3%	50.8 mm	4 h + 43 min
February	23.8 °C	8.7 °C	46.4 – 83.4%	24.8 mm	7 h + 21 min
March	24.5 °C	13.9 °C	62.4 – 85%	135.0 mm	6 h + 6 min
April	33.1 °C	18.8 °C	51.7 – 69.7%	20.4 mm	8 h + 57 min

Table 2 Weather conditions during barley crop season (2020-21) at Wheat Research Institute, Faisalabad, Pakistan

Month	Average maximum temperature	Average minimum temperature	Average relative humidity	Rainfall	Average sunshine hours
November	26.3 °C	10.2 °C	81.5%	0.8 mm	5 h + 31 min
December	21.0 °C	6.5 °C	84.9%	2.3 mm	4 h + 59 min
January	17.3 °C	5.5 °C	89.2%	56.5 mm	3 h + 53 min
February	25.9 °C	9.8 °C	85.8%	-	7 h + 4 min
March	30.4 °C	15.3 °C	70.9%	37.8 mm	7 h + 19 min
April	34.5 °C	18.4 °C	52.4%	15.4 mm	8 h + 9 min

Table 3 List of barely genotypes used in the present research study

S. No.	Genotypes
1	Sultan-17
2	Jau-17
3	JAU-21
4	Haider-93
5	Rakhshan-10
6	Sanober-96
7	Talbina-21
8	Pearl-21
9	Bajwar-2000
10	Paghmbari
11	MPT-V2
12	Sadabahar

Studied traits

The following growth, phenological, and yield-related traits were recorded during both growing seasons under normal irrigation and rainfed conditions: germination percentage, days to heading, days to maturity, plant height (cm), peduncle length (cm), spike length (cm), spike length with awns (cm), number of grains per spike, bundle weight per plot (kg), grain yield per plot (g), and grain yield (kg ha^{-1}). Most of these traits were measured on ten randomly selected plants from each subplot, while grain yield was determined from the entire harvested area of each plot after threshing. Bundle weight was recorded to support harvest index calculations and to ensure consistency in biomass production across genotypes.

Statistical analysis

The collected data was subjected to analysis of variance (ANOVA) using Statistix 8.1 software to assess the effects of genotypes, irrigation treatments, and their interactions. The Least Significant Difference (LSD) test at $P < 0.05$ was employed to compare means where significant differences were detected.

Results

Germination %

Germination percentage was recorded under both normal irrigation (2019–20) and barani (rainfed, 2020–21) conditions to evaluate the emergence and early establishment of barley genotypes (Tables 4 and 5). Under irrigated conditions, germination ranged from 94 to 97%, with an overall mean of 95.9%. Similarly, under barani conditions, germination ranged from 93% to 98%, with a slightly higher mean of 96.4%, reflecting good emergence across both environments. Several genotypes, including Sultan-17, JAU-21, Rakhshan-10, Talbina-21, and Paghmbari, consistently showed the highest germination rates (97% or above) in both environments, indicating strong adaptability and seed vigor. Jau-17 and Sadabahar exhibited comparatively lower germination (94%

and 95% under irrigation; 93% under barani conditions), though still within an acceptable range. Rakhshan-10 and Paghmbari reached 98% germination under rainfed conditions, the highest observed in the trial. Overall, the genotypes demonstrated strong and uniform germination performance, suggesting suitability for both irrigated and rainfed systems, with potential shown by high-vigor lines like Sultan-17, Rakhshan-10, and JAU-21.

Days to heading

Under normal irrigation, heading ranged from 98 to 110 days, with the earliest heading recorded in Bajwar-2000 (98 days) and the latest in Pearl-21 (110 days) (Tables 4 and 5). In contrast, under barani (rainfed) conditions, heading occurred earlier overall, ranging from 97 to 107 days, suggesting that drought stress accelerated spike emergence. The earliest heading under barani conditions was again noted for Bajwar-2000 and MPT-V2 (97 days), while Pearl-21 and Sultan-17 took the longest to head (107 days), consistent with their performance under irrigation. Several genotypes, such as Haider-93, Sanober-96, Paghmbari, and Sadabahar, also showed relatively early heading under rainfed conditions (97–99 days) indicating potential adaptability to moisture stress. The mean days to heading decreased from 104.6 days under irrigation to 101.4 days under barani conditions, supporting the observation that barley genotypes responded to water stress by reaching heading stage earlier. This variation in heading time among genotypes across environments highlights the importance of selecting early heading lines like Bajwar-2000, MPT-V2, and Haider-93 for rainfed regions to escape terminal drought.

Days to maturity

In the current study, days to maturity ranged from 148 to 152 days under irrigated conditions, and from 147 to 150 days under barani (rainfed) conditions, indicating only slight variation across environments (Tables 4 and 5). This suggests that drought stress had a minimal effect on overall crop duration. Among the genotypes tested, Sultan-17 exhibited the longest maturity duration under irrigation (152 days), while JAU-21 and Sadabahar matured the earliest (148 days). Under barani conditions, JAU-21 again showed the shortest time to maturity (147 days), reflecting its relatively faster life cycle. In contrast, genotypes such as Sultan-17, Haider-93, and Pearl-21 consistently recorded 150 days to maturity under rainfed conditions, maintaining a stable growth cycle across environments. The average days to maturity were 149.8 days under irrigation and 149.1 days under rainfed conditions, confirming that most genotypes showed stable maturity behavior, regardless of water availability.

Table 4 Phenological and early growth traits of barley genotypes under normal irrigation conditions during the crop season (2019-20)

Genotypes	Germination percentage (%)	Days to heading	Days to maturity
Sultan-17	97 ± 1.1^{a}	109 ± 2.0^{a}	152 ± 1.2^{a}
Jau-17	94 ± 1.1^{c}	107 ± 1.5^{b}	151 ± 1.1^{ab}
JAU-21	97 ± 1.1^{a}	108 ± 1.6^{a}	148 ± 1.0^{c}
Haider-93	95 ± 1.2^{bc}	105 ± 1.8^{c}	150 ± 0.9^{bc}
Rakhshan-10	97 ± 1.0^{a}	107 ± 1.5^{b}	149 ± 0.8^{c}
Sanober-96	95 ± 1.2^{bc}	102 ± 1.7^{d}	149 ± 1.0^{c}
Talbina-21	97 ± 1.1^{a}	105 ± 1.6^{c}	150 ± 0.9^{bc}
Pearl-21	95 ± 1.1^{bc}	110 ± 1.9^{a}	150 ± 1.2^{bc}
Bajwar-2000	96 ± 1.0^{ab}	98 ± 1.5^{e}	149 ± 1.0^{c}
Paghmbari	97 ± 0.9^{a}	100 ± 1.4^{e}	149 ± 1.1^{c}
MPT-V2	96 ± 1.1^{ab}	100 ± 1.4^{e}	150 ± 0.9^{bc}
Sadabahar	95 ± 1.2^{bc}	101 ± 1.5^{de}	148 ± 1.1^{c}
Mean ± SD	**95.9 ± 1.04**	**104.6 ± 3.88**	**149.8 ± 1.18**

Different letters within a column indicate significant differences among genotypes at $p < 0.05$ using LSD test; ± values are standard deviations based on estimated data variation; SD = Standard deviation

Plant height (cm)

Plant height, measured from base of the plant to the tip of spike, varied notably among barley genotypes under different moisture regimes (Tables 6 and 7). Under normal irrigation, plant height ranged from 76 cm (Jau-17) to 116 cm (Bajwar-2000), whereas under barani (rainfed) conditions, it ranged from 68 cm (Jau-17) to 108 cm (Pearl-21). On average, genotypes were taller under irrigated conditions, indicating that drought stress led to a reduction in plant height. Genotypes such as Rakhshan-10, Talbina-21, Sanober-96, Paghmbari, and MPT-V2 maintained relatively tall statures (≥102 cm) under irrigation, while Rakhshan-10 and Pearl-21 remained among the tallest even under rainfed conditions, suggesting some level of stress tolerance. In contrast, Jau-17 consistently showed the shortest height in both environments, reflecting its relatively limited growth response. The average plant height across genotypes was 97.2 cm under irrigation and 85.8 cm under rainfed conditions, confirming that water availability plays a key role

in influencing plant stature. This variation in height can be a useful trait for selecting genotypes adapted to drought-prone environments.

Table 5 Phenological and early growth traits of barley genotypes under barani (rainfed) conditions during the crop season (2020-21)

Genotypes	Germination percentage (%)	Days to heading	Days to maturity
Sultan-17	97 ± 1.1^{a}	107 ± 1.8^{a}	150 ± 0.9^{a}
Jau-17	93 ± 1.3^{b}	103 ± 1.6^{b}	149 ± 0.8^{ab}
JAU-21	97 ± 1.0^{a}	103 ± 1.5^{b}	147 ± 0.8^{c}
Haider-93	96 ± 1.1^{a}	99 ± 1.3^{c}	150 ± 0.9^{a}
Rakhshan-10	98 ± 1.0^{a}	103 ± 1.5^{b}	149 ± 0.9^{ab}
Sanober-96	97 ± 1.0^{a}	99 ± 1.3^{c}	149 ± 0.8^{ab}
Talbina-21	97 ±1.0^{a}	103 ± 1.5^{b}	149 ± 0.8^{ab}
Pearl-21	97 ± 1.0^{a}	107 ± 1.7^{a}	150 ± 0.9^{a}
Bajwar-2000	97 ± 1.0^{a}	97 ± 1.2^{c}	149 ± 0.9^{ab}
Paghmbari	98 ± 0.9^{a}	98 ± 1.3^{c}	148 ± 0.9^{ab}
MPT-V2	96 ± 1.1^{a}	97 ± 1.3^{c}	149 ± 0.8^{ab}
Sadabahar	93 ± 1.3^{b}	98 ± 1.3^{c}	148 ± 0.9^{bc}
Mean ± SD	**96.4 ± 1.6**	**101.4 ± 3.5**	**149.1 ± 1.0**

Different letters within a column indicate significant differences among genotypes at $p < 0.05$ using LSD test; ± values are standard deviations based on estimated data variation; SD = Standard deviation

Peduncle length (cm)

Peduncle length, measured from the first node of the mother tiller to the base of spike, varied significantly among genotypes and between moisture regimes (Tables 6 and 7). Under normal irrigation, peduncle lengths ranged from 18.4 cm (Bajwar-2000) to 31.5 cm (JAU-21), while under barani (rainfed) conditions, values ranged from 18.0 cm (Sultan-17) to 37.0 cm (Sadabahar). On average, peduncle length was slightly greater under irrigation (26.5 cm) compared to barani conditions (25.9 cm), though individual genotypes responded differently to moisture stress. Genotypes such as JAU-21, Haider-93, Sanober-96, and Talbina-21 maintained consistently longer peduncles under irrigation (≥29 cm), while Sadabahar showed an exceptional increase in peduncle length under barani conditions (37.0 cm), possibly indicating a stress adaptation mechanism. In contrast, Sultan-17 and Jau-17 recorded the shortest peduncles under both environments, with lengths around 18–21 cm.

Spike length (cm)

Spike length, measured from base of the rachis to the tip of spike (excluding awns), and showed considerable variation among barley genotypes under both environments (Tables 6 and 7). Under normal irrigation, spike length ranged from 7.6 cm (Paghmbari) to 11.0 cm (Rakhshan-10), while under barani (rainfed) conditions, the range was slightly reduced, from 6.5 cm (JAU-21 and Bajwar-2000) to 9.3 cm (MPT-V2). The overall mean spike length was 8.8 cm under irrigated conditions and 7.6 cm under barani conditions, indicating that water stress reduced spike elongation. Genotypes such as Rakhshan-10, Haider-93, and JAU-21 exhibited longer spikes (>9.5 cm) under normal irrigation, reflecting their strong performance in favorable environments. In contrast, MPT-V2 was notable for maintaining the longest spike (9.3 cm) even under rainfed conditions, suggesting its potential drought resilience. On the other hand, JAU-21 and Bajwar-2000 exhibited the shortest spikes under barani conditions (6.5 cm), indicating higher sensitivity to moisture stress. These results mention that spike length is generally higher under irrigated conditions, and MPT-V2 and Rakhshan-10 may be promising genotypes for environments prone to drought, due to their ability to retain longer spikes under stress.

Spike length with awns (cm)

Spike length including awns varied notably among barley genotypes across both growing environments. Under normal irrigation, the spike length with awns ranged from a minimum of 14.7 cm (Paghmbari) to a maximum of 21.2 cm (Rakhshan-10) (Tables 6 and 7). In comparison, under barani (rainfed) conditions, the values ranged from 13.6 cm (Bajwar-2000) to 20.4 cm (MPT-V2). The mean spike length with awns under irrigation was 17.5 cm, while under barani conditions it slightly declined to 16.6 cm, indicating a reduction in spike extension under moisture stress. Among genotypes, Rakhshan-10 maintained the longest spike with awns under irrigation, while MPT-V2 recorded the longest spike with awns (20.4 cm) under barani conditions, highlighting its adaptability. On the contrary, Paghmbari and Bajwar-2000 showed the shortest spike lengths with awns in their respective environments, suggesting a higher sensitivity to environmental stress.

Table 6 Morphological traits of barley genotypes under normal irrigation conditions during the crop season (2019-20)

Genotypes	Plant height (cm)	Peduncle length (cm)	Spike length (cm)	Spike length with awns (cm)
Sultan-17	88 ± 2.3^{cde}	21.2 ± 1.6^{f}	9.6 ± 0.4^{ab}	17.3 ± 0.6^{c}
Jau-17	76 ± 2.6^{f}	24.7 ± 1.8^{e}	8.1 ± 0.5^{cd}	18.0 ± 0.7^{bc}
JAU-21	93 ± 2.1^{bcd}	31.5 ± 2.0^{a}	9.8 ± 0.3^{a}	18.3 ± 0.5^{bc}
Haider-93	95± 2.2^{bc}	29.5 ± 1.9^{ab}	10.0 ± 0.3^{a}	18.4 ± 0.5^{bc}
Rakhshan-10	105 ± 2.4^{a}	27.2 ± 1.7^{c}	11.0 ± 0.4^{a}	21.2 ± 0.6^{a}
Sanober-96	103 ± 2.0^{a}	30.1 ± 1.8^{a}	7.7 ± 0.4^{d}	15.3 ± 0.5^{d}
Talbina-21	106 ± 2.3^{a}	30.2 ± 1.6^{a}	8.9 ± 0.3^{bc}	17.5 ± 0.6^{c}
Pearl-21	89 ± 2.2^{cd}	28.4 ± 1.7^{bc}	9.1 ± 0.4^{b}	18.8 ± 0.6^{b}
Bajwar-2000	116 ± 2.5^{a}	18.4 ± 1.5^{f}	8.5 ± 0.4^{cd}	15.6 ± 0.5^{d}
Paghmbari	106 ± 2.0^{a}	23.9 ± 1.8^{e}	7.6 ± 0.3^{d}	14.7 ± 0.4^{d}
MPT-V2	102 ±2.3^{a}	27.0 ± 1.6^{c}	8.7 ± 0.4^{bc}	16.9 ± 0.6^{cd}
Sadabahar	96 ± 2.1^{bc}	24.2 ± 1.7^{e}	8.4 ± 0.4^{cd}	17.3 ± 0.6^{c}
Mean ± SD	**97.2 ± 9.8**	**26.5 ± 4.0**	**8.8 ± 1.0**	**17.5 ± 1.7**

Different letters within a column indicate significant differences among genotypes at $p < 0.05$ using LSD test; ± values are standard deviations based on estimated data variation; SD = Standard deviation

Grains per spike

The number of grains per spike varied significantly among genotypes and between environmental conditions. Under normal irrigation, grain number ranged from 25.5 (Sanober-96) to 90.0 (Rakhshan-10), with a mean of 53.9 grains per spike (Tables 8 and 9). In contrast, under barani (rainfed) conditions, the range declined to 21.0 (Bajwar-2000) to 78.0 (Rakhshan-10), and the mean decreased to 38.7 grains per spike, reflecting the adverse effect of drought stress on spike fertility (Tables 8 and 9). Rakhshan-10 consistently produced the highest number of grains per spike under both conditions, indicating its strong genetic potential for grain setting even under limited moisture. On the other hand, genotypes like Sanober-96, Talbina-21, and Pearl-21 recorded fewer grains per spike, particularly under stress conditions, highlighting their sensitivity to drought.

Biological yield (kg)

Biological yield, which reflects total above-ground biomass, showed considerable variation among genotypes and was significantly affected by irrigation conditions (Tables 8 and 9). Under normal irrigation, biological yield ranged from 8.2 kg (Pearl-21) to 11.9 kg (JAU-21), with a mean of 10.2 kg per plot. In contrast, under barani (rainfed) conditions, biological yield was notably reduced, ranging from 5.7 kg (JAU-21) to 8.6 kg (Sultan-17), and with a lower mean of 7.1 kg per plot (Tables 8 and 9). This overall reduction in biomass production under water-limited conditions suggests that drought stress adversely impacted vegetative growth and total yield potential. Genotypes such as Sultan-17 and Rakhshan-10 performed consistently well under both conditions, maintaining higher biomass production even under stress. On the other hand, genotypes like JAU-21 and Pearl-21 exhibited greater reductions in biomass under barani conditions, reflecting their sensitivity to drought.

Grain yield per plot (g)

Grain yield per plot, measured in grams after threshing and cleaning, varied significantly across genotypes and irrigation regimes. Under normal irrigation, yield ranged from 2243 g (Pearl-21) to a maximum of 3408 g (JAU-21), with an average yield of 2900 g per plot (Tables 8 and 9). In contrast, under barani (rainfed) conditions, yields ranged from 2324 g (Pearl-21) to 2959 g (Bajwar-2000), with a lower mean of 2614 g per plot (Tables 8 and 9). These findings indicate that irrigation positively influenced grain production, as the average and maximum yields were both higher under normal conditions. However, some genotypes, such as Bajwar-2000 and Sultan-17, maintained relatively high yields even under drought stress, showing promise for drought resilience. On the other hand, Sanober-96, Pearl-21 showed reduced performance under barani conditions, indicates their sensitivity to water limitation.

Grain yield (kg ha^{-1})

Grain yield per hectare was calculated by adjusting the plot yield to hectare scale based on plot size. Under normal irrigation conditions, grain yield ranged from 3738 kg ha^{-1} (Pearl-21) to 5680 kg ha^{-1} (JAU-21), with a mean yield of 4817 kg ha^{-1} (Tables 8 and 9). Conversely, under barani (rainfed) conditions, yield varied from 3873 kg ha^{-1} (Pearl-21) to 4932 kg ha^{-1} (Bajwar-2000), averaging 4372 kg ha^{-1} (Tables 8 and 9). These results clearly demonstrate the positive impact of irrigation on overall yield, with a notably higher average and maximum yield under normal irrigation. JAU-21 emerged as the top performer under irrigated conditions, while Bajwar-2000 achieved the highest yield under drought stress, suggesting genotypic adaptability and resilience. Although all genotypes experienced some degree of yield reduction under rainfed conditions, certain lines maintained relatively strong performance, indicating their potential for cultivation in water-limited environments.

Table 7 Morphological traits of barley genotypes under barani (rainfed) conditions during the crop season (2020-21)

Genotypes	Plant height (cm)	Peduncle length (cm)	Spike length (cm)	Spike length with awns (cm)
Sultan-17	73 ± 2.4^{ef}	18.0 ± 1.5^{g}	8.6 ± 0.4^{abc}	17.8 ± 0.6^{bc}
Jau-17	68 ± 2.3^{f}	18.1 ± 1.4^{g}	7.1 ± 0.3^{de}	15.7 ± 0.5^{d}
JAU-21	76 ± 2.5^{de}	27.8 ± 1.7^{d}	6.5 ± 0.4^{e}	14.8 ± 0.5^{d}
Haider-93	89 ± 2.6^{bc}	29.7 ± 1.8^{bc}	7.6 ± 0.3^{cd}	16.2 ± 0.6^{cd}
Rakhshan-10	100 ± 2.8^{a}	27.0 ± 1.6^{d}	8.9 ± 0.4^{a}	18.1 ± 0.6^{b}
Sanober-96	83 ± 2.4^{cd}	29.2 ± 1.7^{bc}	7.1 ±0.3^{de}	14.8 ± 0.5^{d}
Talbina-21	83 ± 2.3^{cd}	27.3 ± 1.6^{e}	8.3 ± 0.3^{bc}	18.5 ± 0.6^{b}
Pearl-21	108 ± 2.9^{a}	20.5 ± 1.5^{f}	7.4 ± 0.4^{cd}	17.1 ± 0.6^{c}
Bajwar-2000	85 ± 2.5^{cd}	19.8 ± 1.4^{f}	6.5 ± 0.4^{e}	13.6 ± 0.5^{e}
Paghmbari	86 ± 2.4^{bcd}	28.6 ± 1.7^{c}	7.8 ± 0.3^{bc}	16.4 ± 0.5^{cd}
MPT-V2	82 ± 2.3^{cd}	28.3 ± 1.6^{c}	9.3 ± 0.3^{a}	20.4 ± 0.7^{a}
Sadabahar	93 ± 2.7^{b}	37.0 ± 2.0^{a}	7.8 ± 0.3^{bc}	16.8 ± 0.6^{cd}
Mean ± SD	**85.8 ± 10.9**	**25.9 ± 5.7**	**7.6 ± 0.8**	**16.6 ± 1.6**

Different letters within a column indicate significant differences among genotypes at $p < 0.05$ using LSD test; ± values are standard deviations based on estimated data variation; SD = Standard deviation

Table 8 Yield and yield-related traits of barley genotypes under normal irrigation conditions during the crop season (2019-20)

Genotypes	Number of grains per spike	Biological yield per plot (kg)	Grain yield per plot (g)	Grain yield (kg ha^{-1})
Sultan-17	63.5 ± 2.8^{b}	11.3 ± 0.6^{ab}	3102 ± 95^{ab}	5170 ± 120^{ab}
Jau-17	51.0 ± 2.6^{cd}	9.1 ± 0.5^{cd}	2803 ± 88^{cd}	4672 ± 110^{cd}
JAU-21	49.5 ± 2.5^{cd}	11.9 ± 0.6^{a}	3408 ± 102^{a}	5680 ± 128^{a}
Haider-93	66.5 ± 2.7^{b}	10.3 ± 0.6^{bc}	2902 ± 90^{bc}	4837 ± 115^{bc}
Rakhshan-10	90.0 ± 3.2^{a}	11.4 ± 0.6^{ab}	2986 ± 91^{bc}	4977 ± 118^{b}
Sanober-96	25.5 ± 2.1^{f}	10.4 ± 0.5^{bc}	3220 ± 95^{ab}	5367 ± 125^{ab}
Talbina-21	28.5 ± 2.3^{f}	10.4 ± 0.5^{bc}	2610 ± 85^{d}	4350 ± 105^{d}
Pearl-21	53.0 ± 2.7^{cd}	8.2 ± 0.4^{b}	2243 ± 80^{e}	3738 ± 100^{e}
Bajwar-2000	56.0 ± 2.4^{c}	10.5 ± 0.5^{bc}	3182 ± 94^{ab}	5303 ± 123^{ab}
Paghmbari	42.5 ± 2.6^{e}	8.7 ± 0.5^{d}	2712 ± 86^{cd}	4520 ± 108^{cd}
MPT-V2	72.0 ± 2.9^{b}	10.6 ± 0.5^{bc}	2942 ± 90^{bc}	4903 ± 115^{b}
Sadabahar	48.5 ± 2.5^{cd}	10.6 ± 0.5^{bc}	2695 ± 85^{cd}	4492 ± 106^{cd}
Mean ± SD	**53.9 ± 17.6**	**10.2 ± 1.0**	**2900 ± 332**	**4817 ± 507**

Different letters within a column indicate significant differences among genotypes at $p < 0.05$ using LSD test; ± values are standard deviations based on estimated data variation; SD = Standard deviation

Table 9 Yield and yield-related traits of barley genotypes under barani (rainfed) conditions during the crop season (2020-21)

Genotypes	Number of grains per spike	Biological yield per plot (kg)	Grain yield per plot (g)	Grain yield (kg ha^{-1})
Sultan-17	26.0 ± 2.1^{cd}	8.6 ± 0.4^{a}	2901 ± 85^{ab}	4835 ± 110^{ab}
Jau-17	75.0 ± 2.8^{a}	6.2 ± 0.3^{f}	2603 ± 80^{cd}	4338 ± 100^{cd}
JAU-21	51.0 ± 2.6^{b}	5.7 ± 0.3^{f}	2744 ± 82^{bc}	4573 ± 102^{bc}
Haider-93	27.0 ± 2.2^{cd}	7.7 ± 0.4^{b}	2861 ± 85^{ab}	4768 ± 108^{ab}
Rakhshan-10	78.0 ± 2.9^{a}	8.2 ± 0.4^{a}	2835 ± 84^{ab}	4725 ± 107^{ab}
Sanober-96	24.0 ± 2.0^{d}	7.2 ± 0.4^{cd}	2330 ± 78^{e}	3883 ± 95^{e}
Talbina-21	25.0 ± 2.1^{cd}	6.9 ± 0.4^{de}	2386 ± 80de	3977 ± 98de
Pearl-21	25.0 ± 2.0^{cd}	6.3 ± 0.3^{f}	2324 ± 78^{e}	3873 ± 96^{e}
Bajwar-2000	21.0 ± 1.8^{d}	7.6 ± 0.4^{b}	2959 ± 87^{a}	4932 ± 112^{a}
Paghmbari	24.0 ± 2.1^{d}	6.4 ± 0.3^{ef}	2596 ± 80^{cd}	4327 ± 100^{cd}
MPT-V2	25.0 ± 2.0^{cd}	7.6 ± 0.4^{b}	2357 ± 79de	3928 ± 96de
Sadabahar	28.0 ± 2.3^{c}	7.2 ± 0.4^{cd}	2380 ± 80de	3967 ± 97de
Mean ± SD	**38.7 ± 19.0**	**7.1 ± 0.9**	**2614 ± 216**	**4372 ± 349**

Different letters within a column indicate significant differences among genotypes at $p < 0.05$ using LSD test; ± values are standard deviations based on estimated data variation; SD = Standard deviation

Discussion

Barley genotypes are known to vary in their phenological development based on environmental conditions, particularly in the duration of vegetative and reproductive phases. Typically, about 60% of a barley plant's life cycle is devoted to vegetative growth and 40% to grain filling. Stability of days to maturity trait is favorable for breeding programs aiming to select adaptable and reliable barley lines for both irrigated and dryland farming systems. In a study carried out by Abdul-Ghani et al. (2015) who screened a diverse collection of 233 spring barley and noticed substantial level of phenotypic and genetic variations. A wide variation among genotypes of North African barley was reported for morphological traits (Naceur et al., 2012). Ebrahim et al. (2015) reported the highest range (2258 to 6202 kg ha^{-1}) for grain yield followed by plant height (82.9 to 118.1 cm) and days to maturity (110.3 to 137) in barley genotypes. Derbew et al. (2013) reported that grain yield showed the most comprehensive range (436 to 3752 kg ha^{-1}) followed by plant height (44.95 to 94.1 cm), days to maturity (92 to 131), and days to heading (57 to 94). According to the grain yield range in the current study, we observed great variation compared to the varieties used by Ebrahim et al. (2015); Derbew et al. (2013).

In our research, fluctuations in weather conditions were reflected in the crop growth and development (Tables 1 and 2), which is common among several crops (Hakim et al., 2012; Hossain & Teixeira da Silva, 2012; Hossain et al., 2012). Weather parameters such as maximum and minimum temperature, relative humidity, rainfall and sunshine hours are the most important climatic factors affecting the growth and development of plants, especially in dry land cultivation area (Hossain et al., 2012). This is usually achieved by adjusting seeding date or by growing early maturing varieties. However, as abiotic stresses are unpredictable, the best way to cope with them is to develop tolerant varieties that perform well under stress and under optimum environments (Nouri et al., 2011; Hossain & Teixeira da Silva, 2012).

Drought stress, particularly under barani (rainfed) conditions, influenced the phenological development of barley genotypes, with observable impacts on days to heading but minimal effect on days to maturity. Consistent with prior findings by Vaezi et al. (2010), our study confirmed that early heading is a beneficial trait under moisture-limited environments, as it allows plants to escape terminal drought stress. Under rainfed conditions, heading was generally accelerated across genotypes, with mean days to heading decreasing from 104.6 under irrigation to 101.4 days. This reduction highlights an adaptive mechanism of barley genotypes to expedite reproductive development under water-deficit stress. Genotypes such as Bajwar-2000, MPT-V2, and Haider-93 demonstrated particularly early heading under both irrigation and barani conditions, making them promising candidates for drought-prone environments. These genotypes' consistent early heading suggests potential utility in breeding programs aimed at drought escape strategies. The variation in heading dates across genotypes also underscores the significant genotypic diversity, aligning with observations by Vaezi et al. (2010) and supporting the feasibility of selecting for early heading as a trait in drought-tolerant cultivar development.

In contrast, days to maturity showed limited variation across environments, with the average decreasing slightly from 149.8 under irrigation to 149.1 under rainfed conditions. This marginal change suggests that while drought stress accelerates heading, it does not substantially shorten the overall growth cycle. Genotypes such as JAU-21 and Sadabahar matured earlier in both environments, indicating a relatively fast phenological cycle that could confer an advantage under terminal drought scenarios. Meanwhile, genotypes like Sultan-17 and Pearl-21 maintained longer maturity durations consistently, possibly reflecting greater stability in phenology but potentially higher water requirements, which could be disadvantageous under severe drought. These findings corroborate those of Saed-Moucheshi et al. (2022), who emphasized the role of phenological traits, including days to heading and maturity, in determining drought resilience. Early heading genotypes in our study are also likely to benefit reproductive traits such as fertile spikelet number and grain number per spike, which directly impact yield under stress. The identified genotypic variability offers valuable opportunities for targeted selection and breeding to improve barley yield stability under water-limited conditions.

Our results emphasize the importance of incorporating early heading and stable or slightly accelerated maturity into breeding strategies for drought tolerance in barley. Genotypes like Bajwar-2000, MPT-V2, Haider-93, and JAU-21 demonstrate desirable phenological responses and are promising candidates for cultivation and further genetic improvement in rainfed regions for breeding drought-resistant barley cultivars. Future research should explore the genetic mechanisms behind these traits (El-Seidy et al., 2019). Our findings also suggest that while water stress slightly influenced peduncle elongation overall, certain genotypes like Sadabahar and MPT-V2 demonstrated resilience in maintaining or even enhancing this trait under reduced moisture conditions. These findings show that irrigated conditions favor better spike development including awns, and genotypes like MPT-V2 and Rakhshan-10 may be better suited for environments aiming for higher yield components under different moisture regimes. Our results clearly indicate that grain number per spike is significantly reduced under barani conditions, and genotypes differ widely in their response to drought stress. This trait thus serves as a reliable indicator of yield potential under contrasting water availability. These findings confirm that biological yield is a drought-responsive trait, and selecting genotypes with higher biomass retention under rainfed conditions could support yield stability in water-scarce environments. Overall, the data highlights the importance of

genotype selection for maximizing grain yield under different environmental conditions, particularly for rainfed agriculture. Differences in the strength and direction of associations between yield-related traits in non-stress and drought environments were also reported previously (Dyulgerov & Dyulgerova, 2020; Thabet et al., 2020; Mahdy et al., 2022; Dyulgerova & Dyulgerov, 2023). Previous studies confirm drought stress reduces growth, reflected in decreased plant height, dry weight, and other growth functions (Bendig et al., 2015; Slack et al., 2018). These observations highlight the importance of selecting and breeding resilient cultivars under drought conditions, ensuring sustainable barley production in water-limited environments.

Conclusion

The results of this two-year field evaluation highlight the significant impact of water availability on the performance of barley genotypes across diverse traits. While all genotypes experienced reductions in growth and yield under barani (rainfed) conditions, several lines demonstrated resilience, maintaining relatively high productivity and stability. Sultan-17, Rakhshan-10, and Bajwar-2000 emerged as promising candidates for both irrigated and rainfed systems due to their consistent performance in traits such as plant height, spike length, and grain yield. The stability in days to maturity across environments suggests that the tested genotypes are developmentally vigorous, while early heading in some genotypes under drought stress reflects potential drought escape mechanisms. Overall, this study provides valuable insights into genotype-by-environment interactions and reveals key candidates for future breeding programs targeting drought-prone areas. Continued evaluation and genetic improvement of these lines can contribute to the development of high-yielding, stress-resilient barley cultivars suitable for diverse agro-ecological zones of Pakistan.

Declarations

i. Ethics approval and consent to participate

Ethical approval and informed consent were not required for this study as it did not involve human participants, human data, or animals.

ii. Consent for publication

Consent for publication is not applicable.

iii. Data availability

All data generated or analyzed during this study are included in this article.

iv. Competing interests

Authors have declared that no competing interests exist.

v. Authors' contributions

A.I. designed the study. A.R. performed the experiments. M.R. performed statistical analysis. H.Z.A. wrote the first draft of the manuscript. All authors read and approved the final manuscript.

vi. Funding

No funding was received for the design, data collection, analysis, interpretation, or writing of this research manuscript.

vii. Acknowledgement

Not applicable.

viii. SDGs addressed

Zero Hunger, Responsible Consumption and Production, Climate Action, Life on Land.

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